Recap of the Nocibur experiment:

High efficiency energy extraction in a strongly tapered undulator

Nicholas Sudar

Advanced Accelerator Concepts 2016

Overview

UCLA

Introduction to Nocibur

- Rubicon backwards: Inverse Inverse Free Electron Laser mechanism

Motivation

- Using strong undulator tapering for high extraction efficiency

The experiment

- The set-up, the results

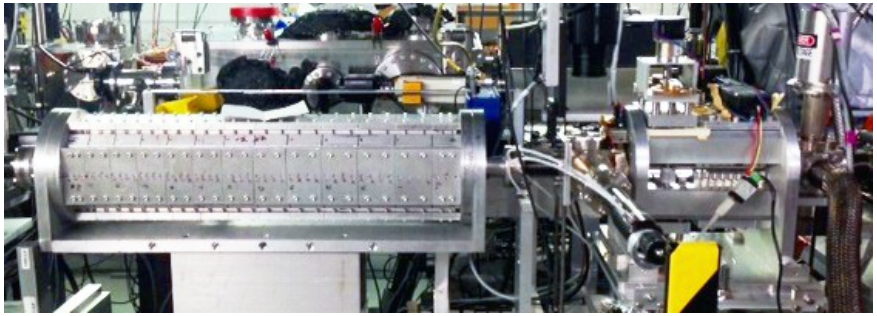
Future plans

- re-circulated Nocibur: measure some gain

Conclusion

The Nocibur Inverse Inverse Free Electron Laser

The IIFEL



From IFEL to IIFEL

- Resonant energy exchange between a laser and electron beam inside of a tapered undulator:

$$\frac{\partial \gamma^2}{\partial z} = -2kK_l K \sin(\Psi) = \frac{\partial}{\partial z}\left(\frac{k(1+K^2)}{2k_w}\right) \qquad K_l = \frac{e\lambda E(z)}{2\pi mc^2} \qquad K = \frac{e\lambda_w(z) B(z)}{2\pi mc}$$

gradient phase synchronicity

- choose design “resonant” phase and energy to satisfy above equation
  - ψr < 0 → accelerating ψr > 0 → decelerating
- Rubicon IIFEL: Helical halbach undulator – CO2 laser seed – BNL ATF
  - 52 MeV → 92 MeV
- Nocibur: reverse Rubicon IIFEL and re-tune
  - 65 MeV → 35 MeV
- IIFEL vs. FEL
  - Post saturation regime: bunched beam, re-focused large seed, strong tapering for optimized energy extraction, stimulated emission: $(E_{seed} + E_{gain})^2 - (E_{seed})^2 = 2E_{seed} * E_{gain} + (E_{gain})^2$

UCLA

The IIFEL Why?

- FEL efficiency: proportional to ρ < 0.5%
- Tapering: extend FEL past saturation, increase efficiency
- ELF experiment: GHz frequencies – waveguide ~ 30% efficiency
- PALADIN: no waveguide optical wavelengths
- XFEL: tapering for TW level
  - TESSA
- Potential compact EUV radiation source
- Nocibur: Low gain regime of TESSA scheme. Demonstrate high extraction efficiency in "optical regime"

1988-90: LLNL 10.6μm Paladin Expt.

- Based on 45-MeV Advanced Test Accelerator
  - designed for 10-kA charged particle beam propagation experiments, not for 1-2 kA high brightness applications
- Paladin Goals:
  - no waveguide ➡ gain&refractive guiding effects critical ✔
  - technological proof for undulator lengths >= 25 m ✔
  - "curved" pole tip focusing worked ✔
  - demonstrate tapering scaled as expected to "optical" regime ✗
  - demonstrate (to "Star Wars" program managers) that high-efficiency, high charge/pulse induction linacs had sufficient brightness to drive single-pass, optical FELs ✗

PALADIN tapering results: *very* disappointing!

High efficiency, multiterawatt x-ray free electron lasers

C. Emma, K. Fang, J. Wu, and C. Pellegrini
Phys. Rev. Accel. Beams **19**, 020705 – Published 26 February 2016

New Journal of Physics
The open access journal at the forefront of physics

DPG IOP Institute of Physics

PAPER

Tapering enhanced stimulated superradiant amplification

J Duris[1], A Murokh[2] and P Musumeci[1]

Tapered undulators for SASE FELs ☆

William M. Fawley[a], Zhirong Huang[b], Kwang-Je Kim[b], Nikolai A. Vinokurov[c]

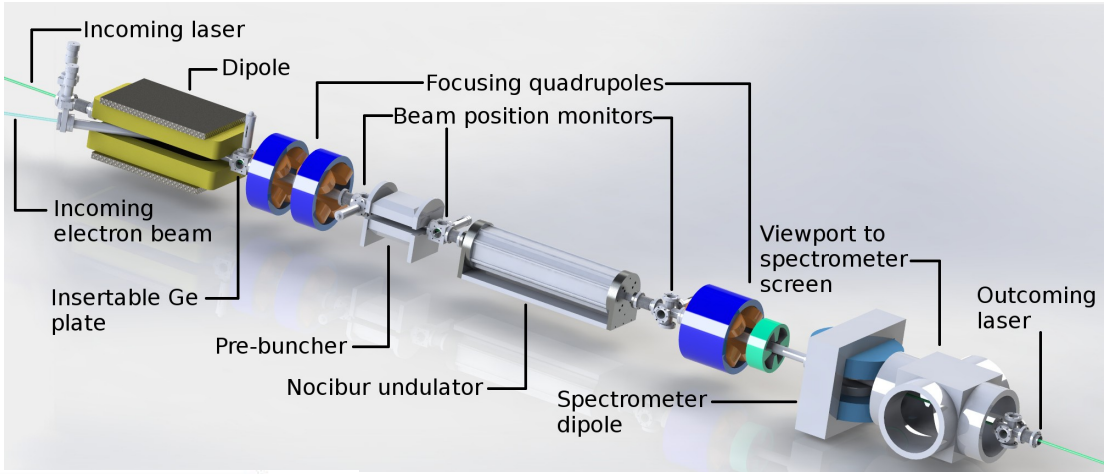
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 050704 (2012)

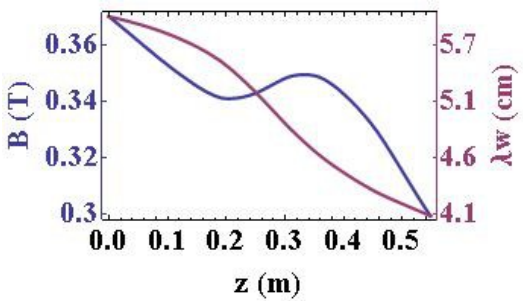
Modeling and multidimensional optimization of a tapered free electron laser

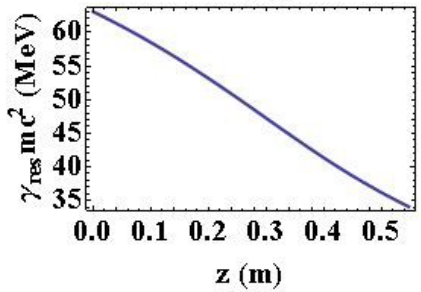
Y. Jiao,[1,2,*] J. Wu,[1,†] Y. Cai,[1] A. W. Chao,[1] W. M. Fawley,[1] J. Frisch,[1] Z. Huang,[1] H.-D. Nuhn,[1] C. Pellegrini,[1,3] and S. Reiche[4]

The experiment

E-Beam energy	65 → 35 MeV
emittance	2 mm-mrad
σxy (waist)	100 μm
Laser Wavelength	10.3 μm
Rayleigh Range	0.3 m
Laser Waist	1 mm
Laser Power	200 GW
E-beam current	100 A
E-beam charge	100 pC
λw buncher	0.05 m (1 period)
Chicane: R56	21 → 59 μm
period tapering	0.06 - 0.04 m
K tapering	2.01 - 1.19



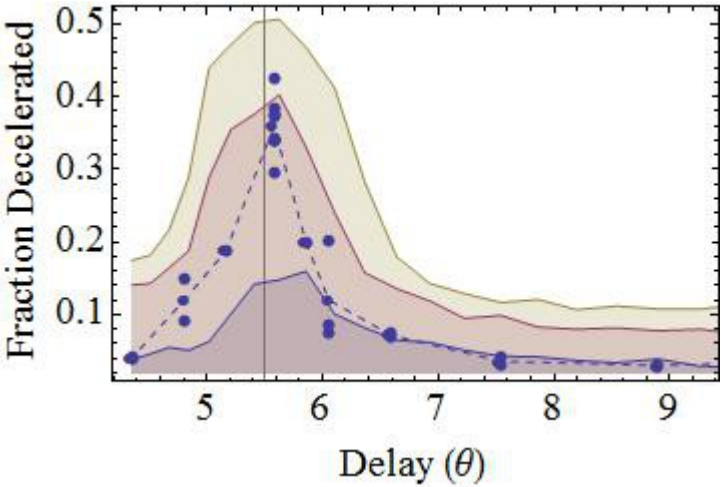


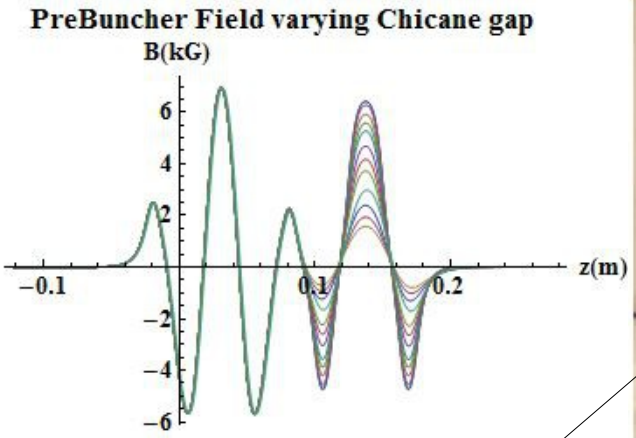


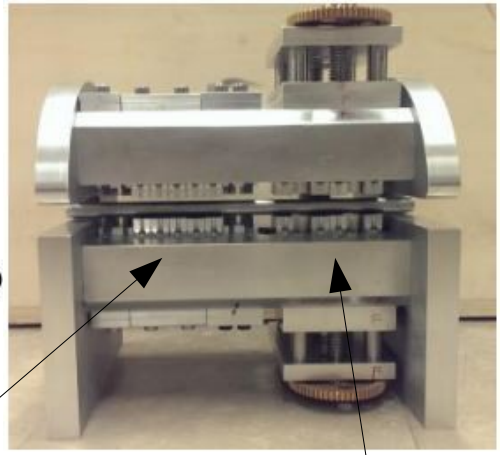
- Laser focused by 4.5 m NaCl lens
- e-beam focused by quadrupole doublet
- Laser e-beam timing: Ge switch
- fine timing: scan delay stage
- optimize injection phase: scan pre-buncher R56
- measure e-beam spectrum on phosphor screen

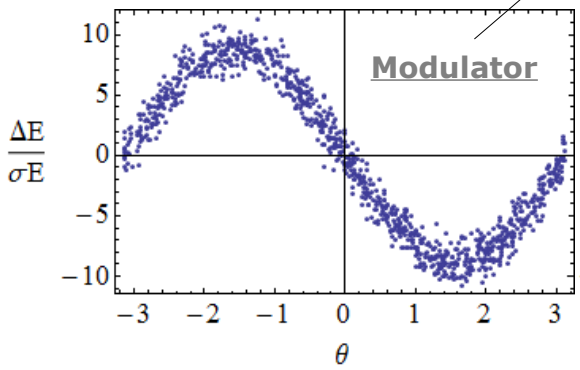
Pre Buncher

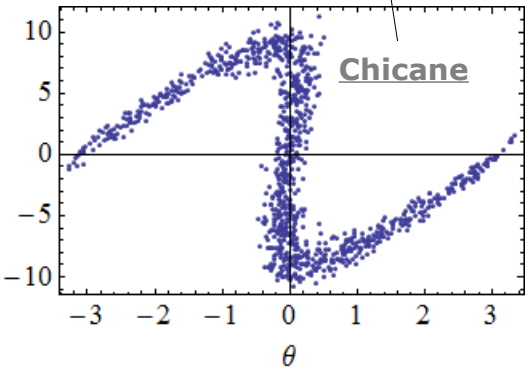
- Single period, planar, halbach undulator
  - Permanent magnet, variable gap chicane
- Laser imparts sinusoidal energy modulation
- Chicane dispersion converts to density modulation
- Chicane delay allows for control of injection phase











The experiment

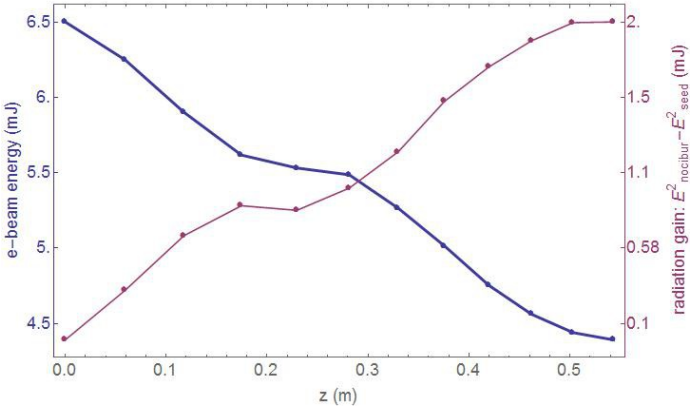
Some results

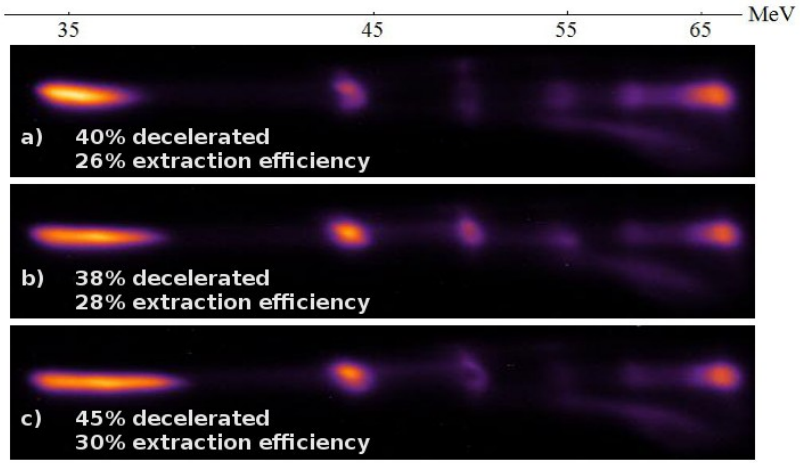
- 45% of particles decelerated from 65 → 35 MeV
- 30% conversion efficiency
- good agreement with GPT simulations
- couldn't measure radiation growth

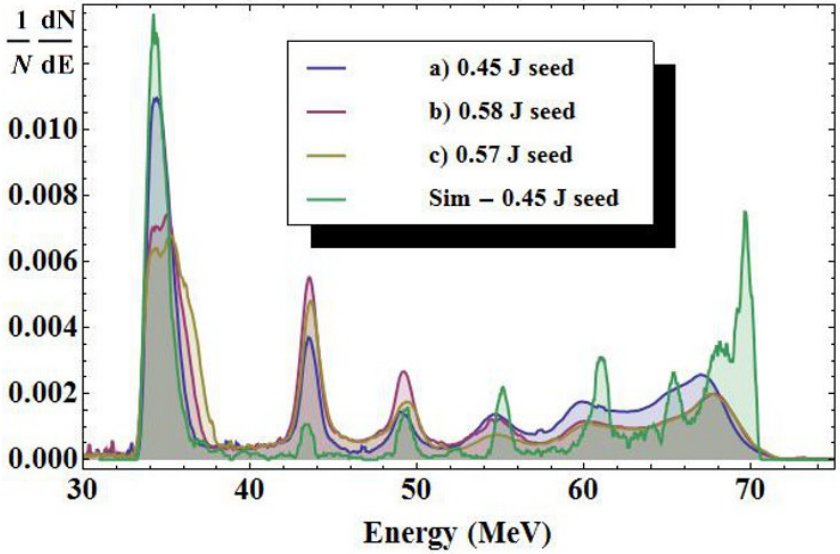
hindered by large seed – broke a pyro camera trying

- Genesis simulations show expected radiation

growth for electron beam energy loss





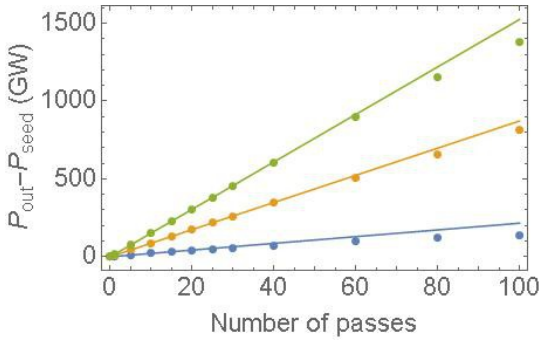


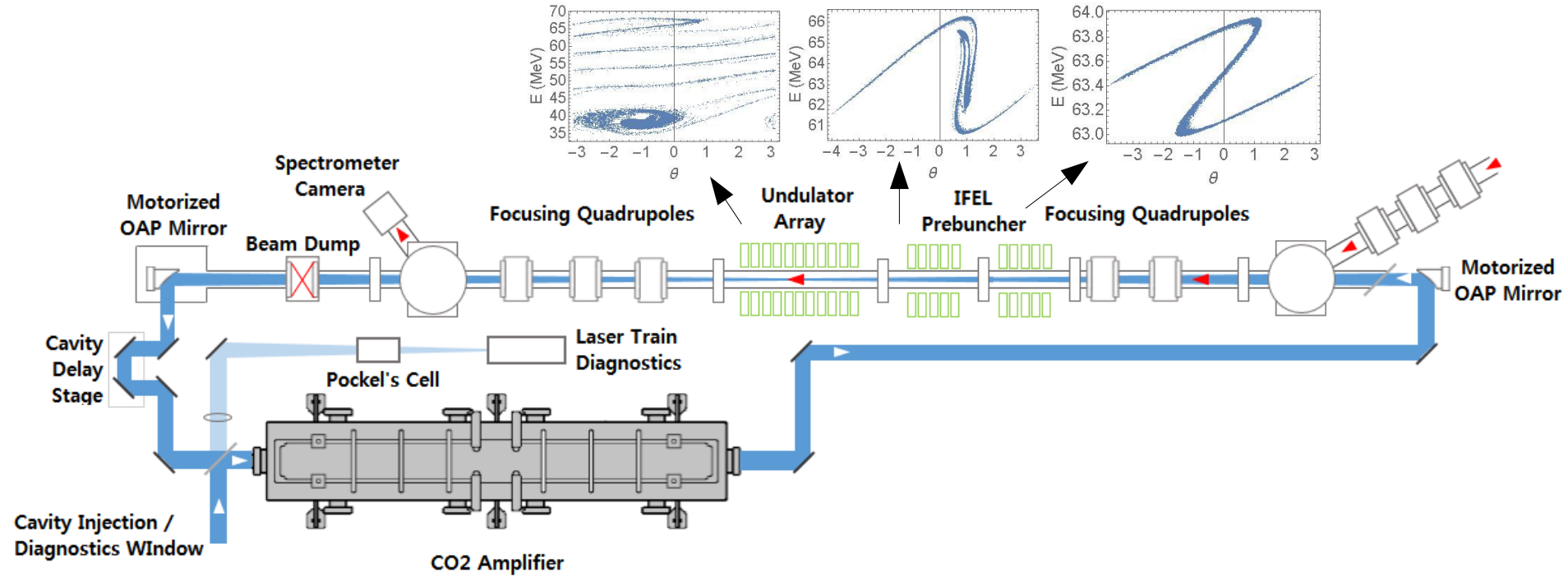
Potential future projects at ATF

rNocibur (cavity gain)

Measure gain from high efficiency Nocibur interaction via recirculation scheme

Increase efficiency with double buncher (90% decelerated – 40% efficiency)





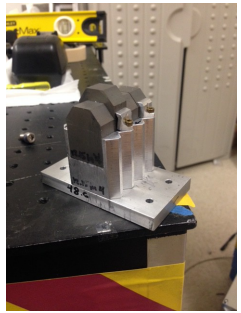
Conclusions

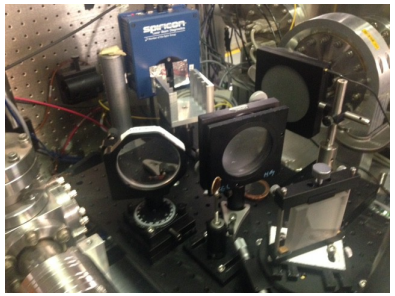
- Demonstrated 30% extraction efficiency in a laser driven strongly tapered undulator interaction: Low gain regime of TESSA mechanism

- High gain regime: requires a longer undulator and a brighter beam.

- Could potentially measure accumulated gain in recirculation scheme

Trials & tribulations





UCLA

PRL 117, 174801 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

High Efficiency Energy Extraction from a Relativistic Electron Beam in a Strongly Tapered Undulator

N. Sudar, P. Musumeci, J. Duris, and I. Gadjev
Particle Beam Physics Laboratory, Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095, USA

M. Polyanskiy, I. Pogorelsky, M. Fedurin, C. Swinson, K. Kusche, and M. Babzien
Accelerator Test Facility, Brookhaven National Laboratory, Upton, New York 11973, USA

A. Gover
Faculty of Engineering, Department of Physical Electronics, Tel-Aviv University, Tel-Aviv 69978, Israel
(Received 3 May 2016; published 19 October 2016)

UCLA: P. Musumeci, J. Duris, I. Gadjev, Y. Sakai

ATF: I. Pogorelsky, M. Polyanskiy, M. Fedurin, C. Swinson, M. Babzien, K. Kusche, M. Montemagno, P. Jacob, G. Stenby, B. Malone, M. Palmer

Radiabeam: A. Murokh

Work supported by: U.S. DHS DNDO under Contract No. 2014-DN-077-ARI084-01, NSF grant 145583 and DOE grant No. DE-SC0009914

Thanks